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(54) **PROCEDURE FOR ETCH RATE
CONSISTENCY**

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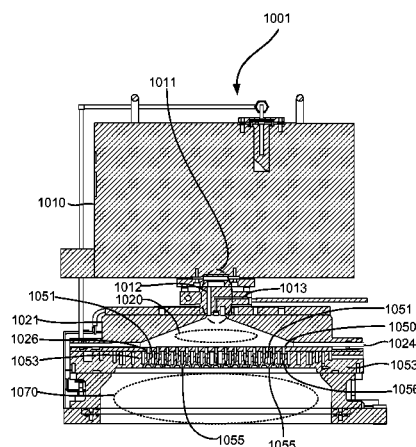
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ABSTRACT

Methods of conditioning interior processing chamber walls of an etch chamber are described. A fluorine-containing precursor may be remotely or locally excited in a plasma to treat the interior chamber walls periodically on a preventative maintenance schedule. The treated walls promote an even etch rate when used to perform gas-phase etching of silicon regions following conditioning. Alternatively, a hydrogen-containing precursor may be remotely or locally excited in a plasma to treat the interior chamber walls in embodiments. Regions of exposed silicon may then be etched with more reproducible etch rates from wafer-to-wafer. The silicon etch may be performed using plasma effluents formed from a remotely excited fluorine-containing precursor.

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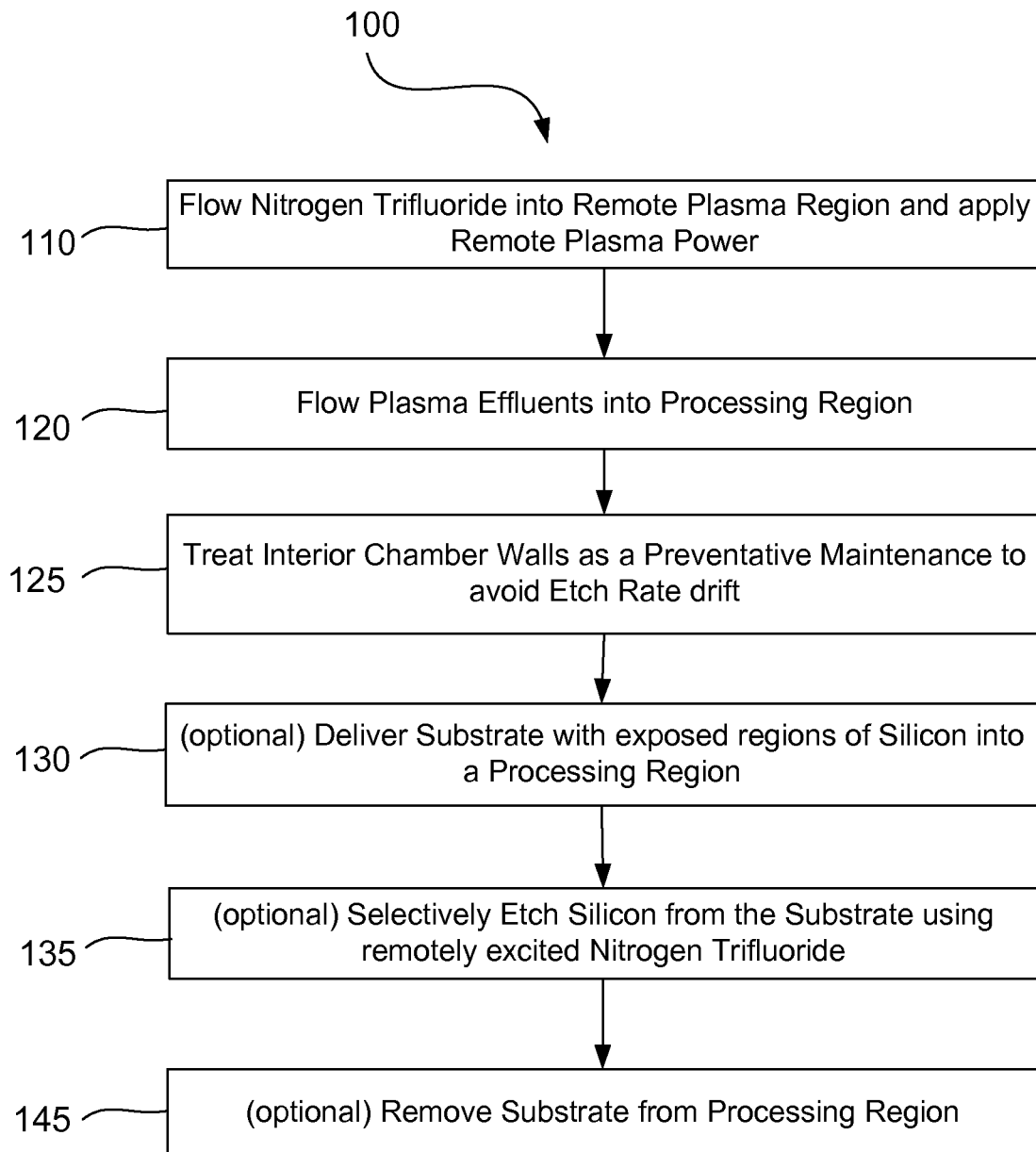
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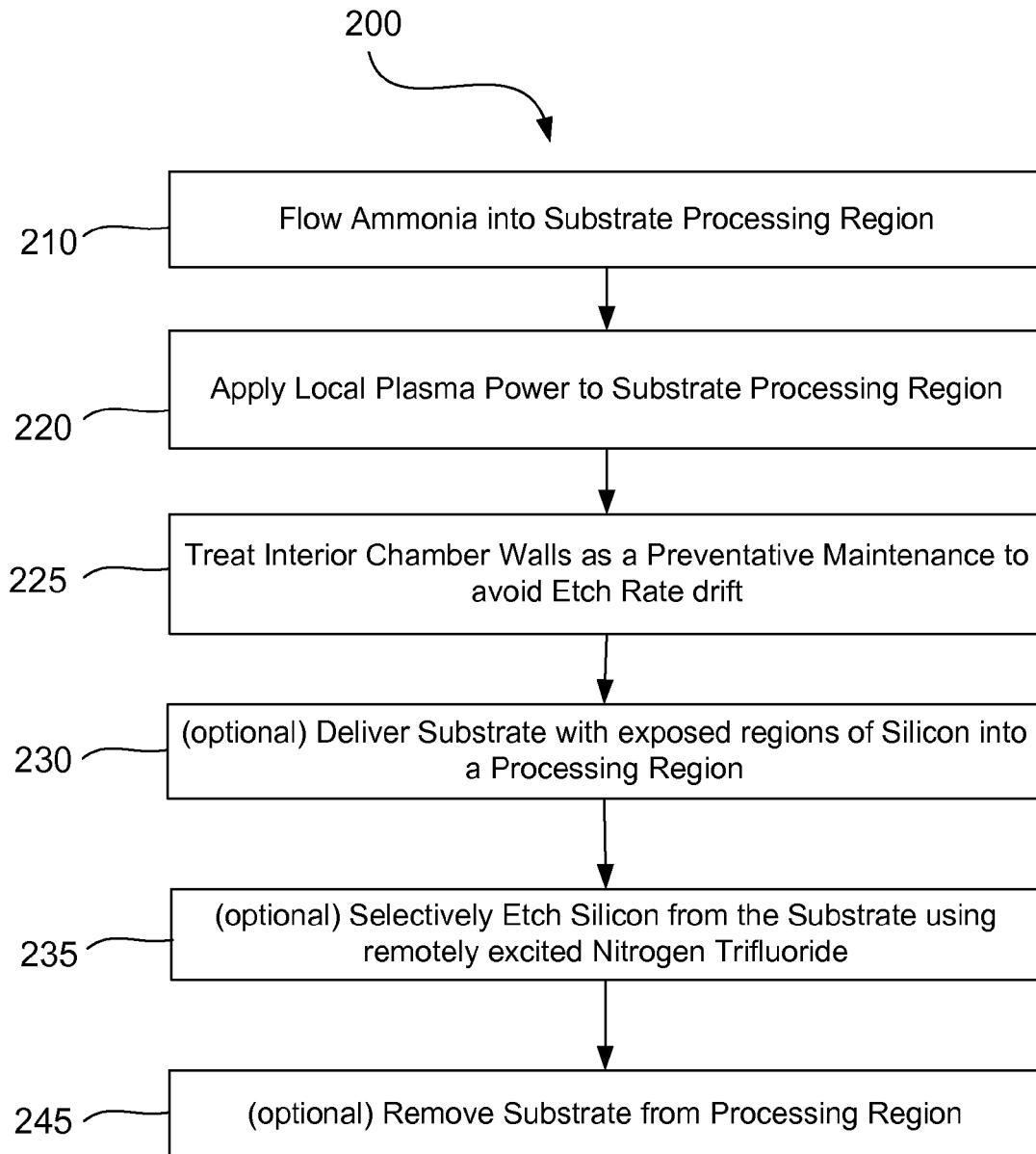
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**FIG. 1**

**FIG. 2**

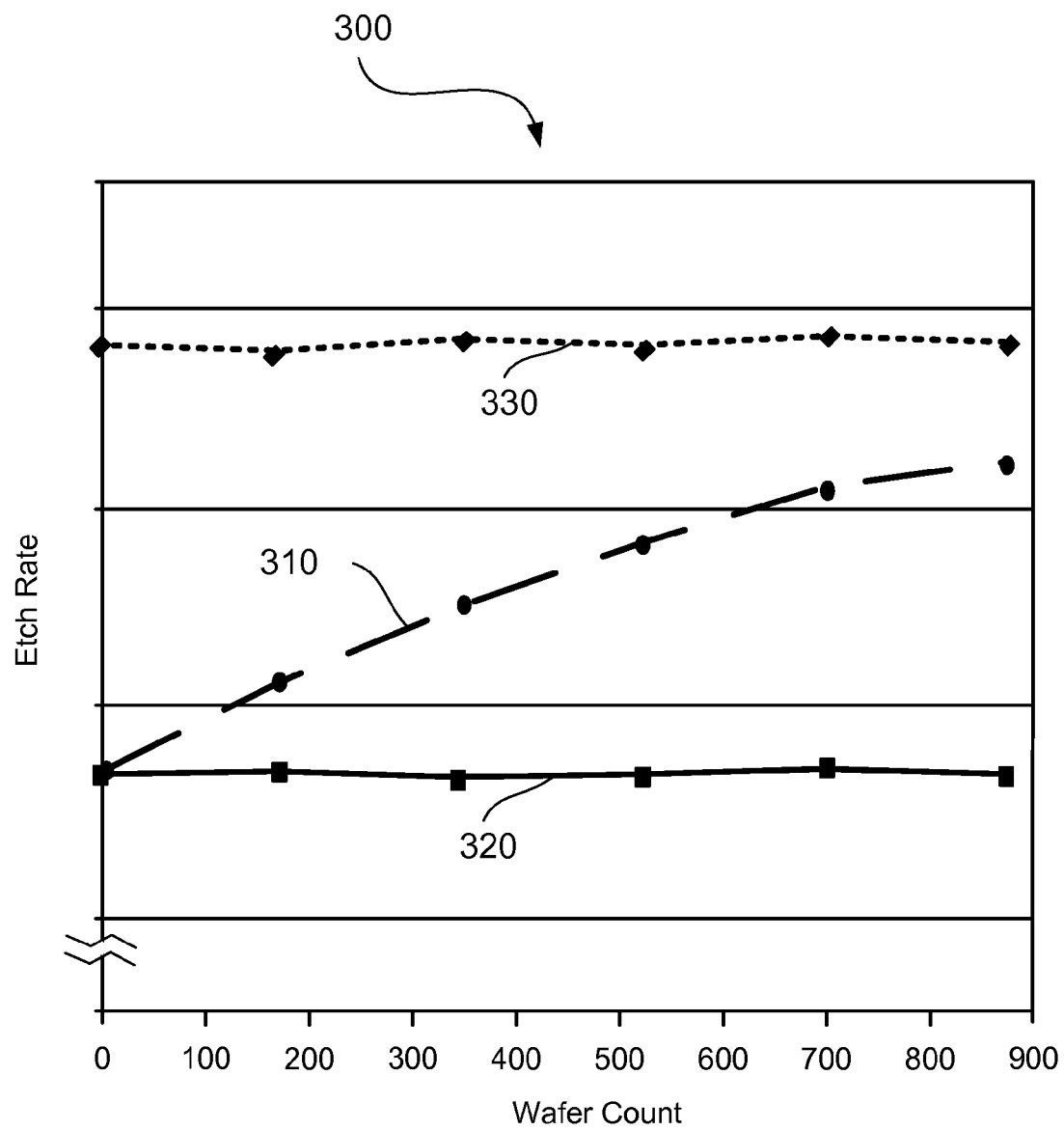


FIG. 3

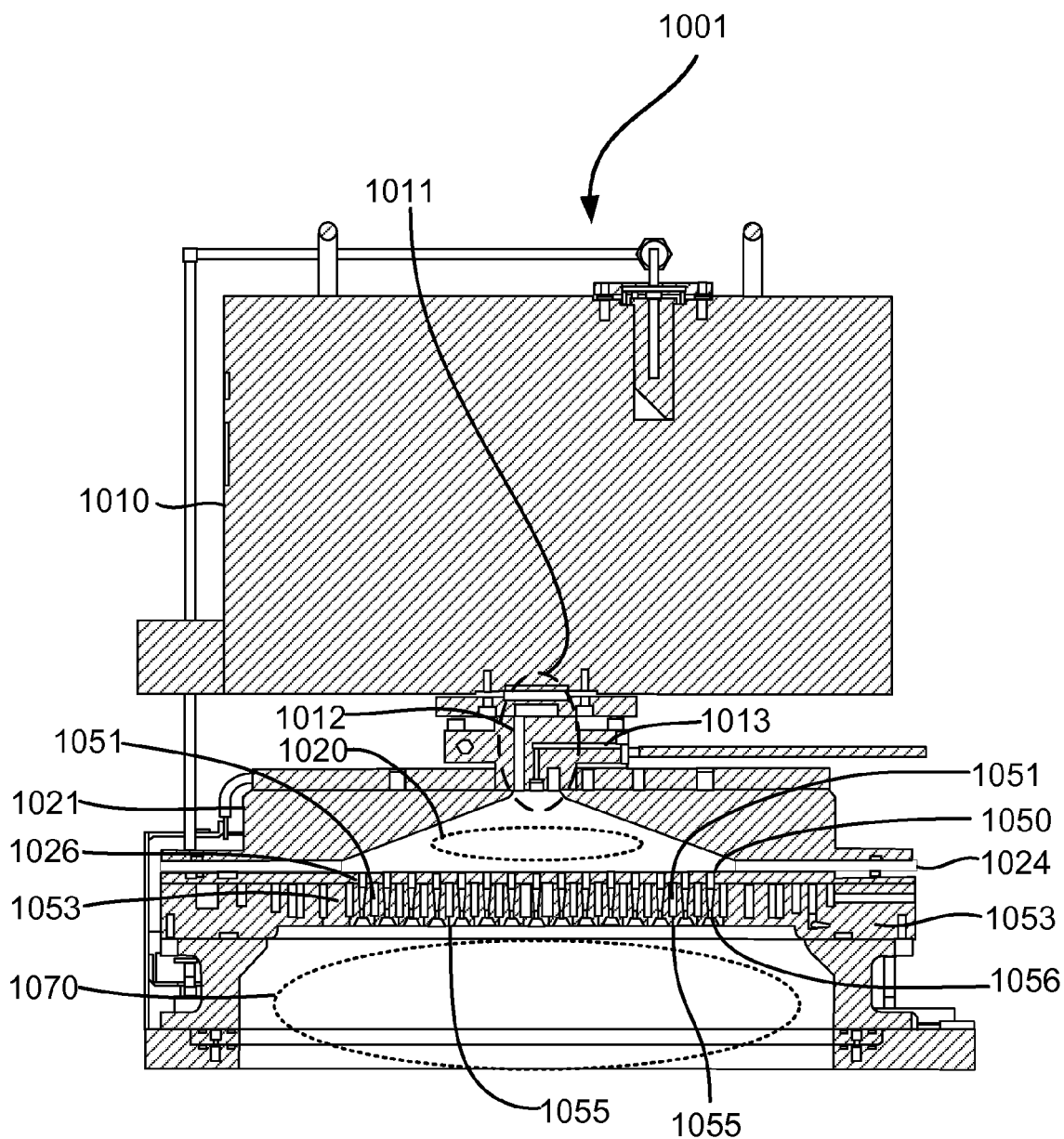


FIG. 4A

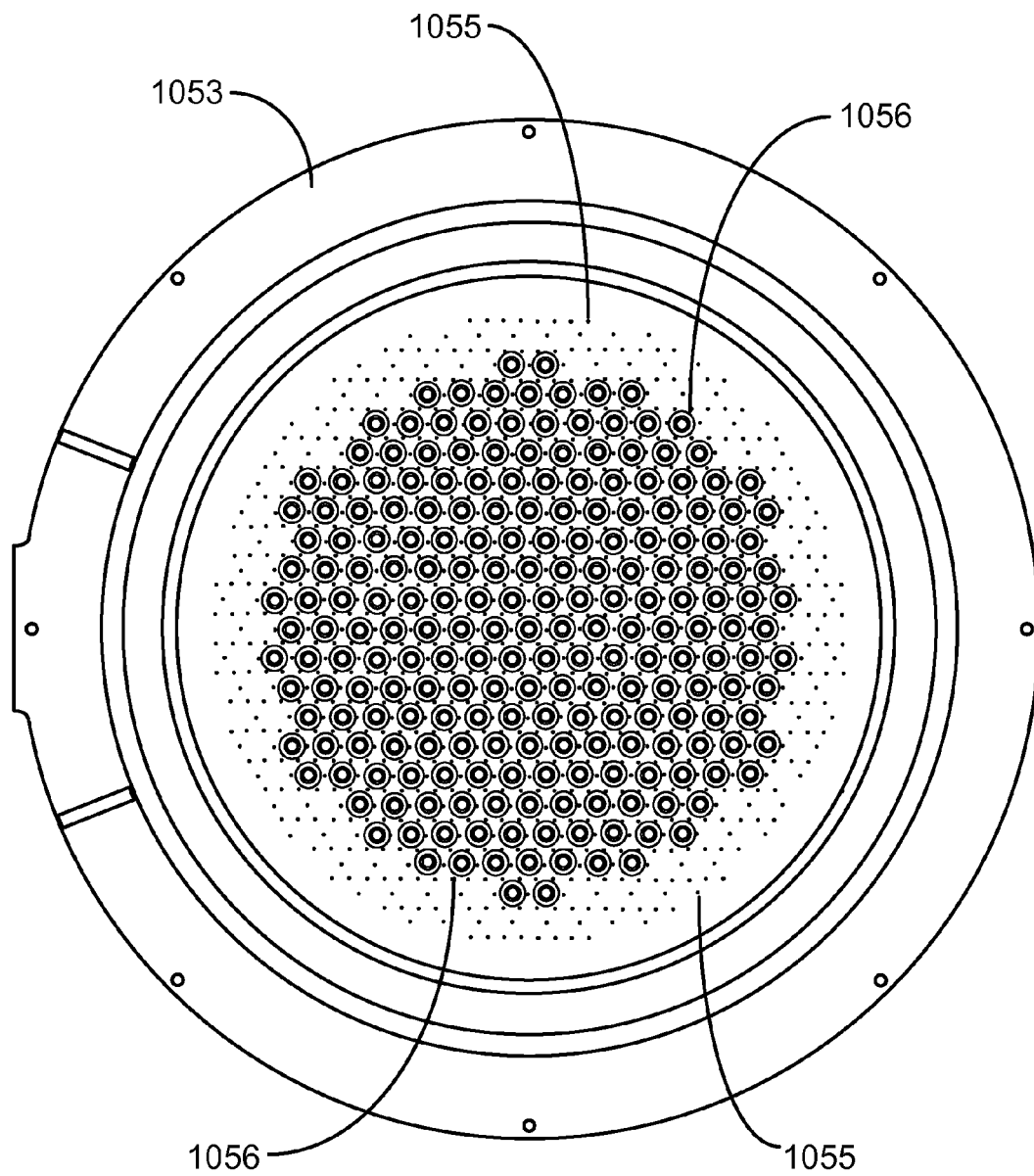


FIG. 4B

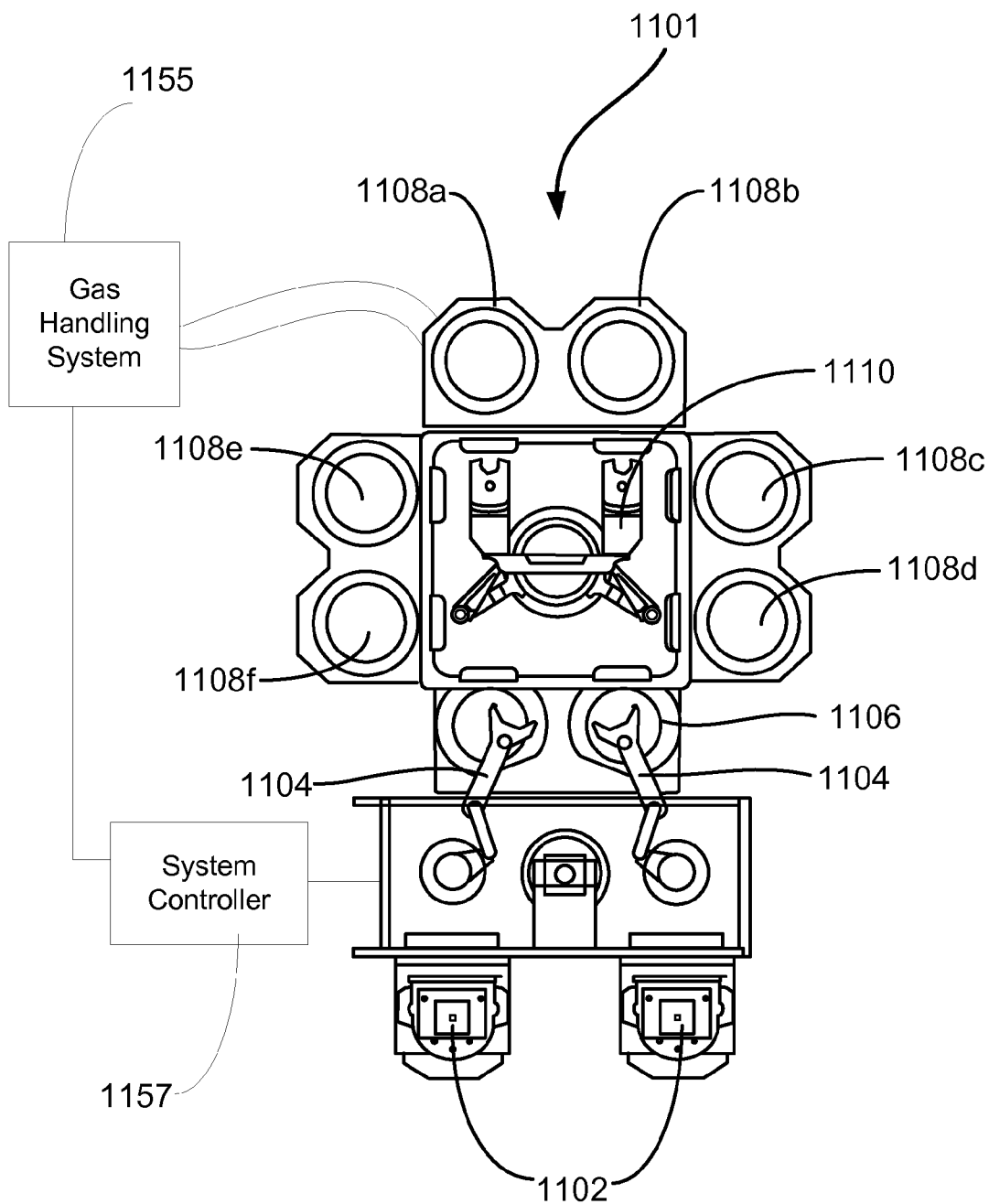


FIG. 5

1

PROCEDURE FOR ETCH RATE CONSISTENCY

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a divisional of Ser. No. 14/275,693, filed May 12, 2014, which claims the benefit of U.S. Prov. Pat. App. No. 61/910,830 by Zhang et al., filed Dec. 2, 2013, and titled "PROCEDURE FOR ETCH RATE CONSISTENCY," which is hereby incorporated herein by reference and in its entirety for all purposes.

FIELD

Embodiments of the invention relate to conditioning a substrate processing region.

BACKGROUND

Integrated circuits are made possible by processes which produce intricately patterned material layers on substrate surfaces. Producing patterned material on a substrate requires controlled methods for removal of exposed material. Chemical etching is used for a variety of purposes including transferring a pattern in photoresist into underlying layers, thinning layers or thinning lateral dimensions of features already present on the surface. Often it is desirable to have an etch process which etches one material faster than another helping e.g. a pattern transfer process proceed. Such an etch process is said to be selective of the first material. As a result of the diversity of materials, circuits and processes, etch processes have been developed that selectively remove one or more of a broad range of materials. However, there are few options for selectively etching silicon using gas phase reactants.

Dry etch processes are often desirable for selectively removing material from semiconductor substrates. The desirability stems from the ability to gently remove material from miniature structures with minimal physical disturbance. Dry etch processes also allow the etch rate to be abruptly stopped by removing the gas phase reagents. Some dry-etch processes involve the exposure of a substrate to remote plasma by-products formed from one or more precursors. For example, remote plasma generation of nitrogen trifluoride in combination with ion suppression techniques enables silicon to be selectively removed from a patterned substrate when the plasma effluents are flowed into the substrate processing region. However, process improvements are needed to improve the utility of these remote plasma processes.

Methods are needed to maintain consistent silicon etch rates.

SUMMARY

Methods of conditioning interior processing chamber walls of an etch chamber are described. A fluorine-containing precursor may be remotely or locally excited in a plasma to treat the interior chamber walls periodically on a preventative maintenance schedule. The treated walls promote an even etch rate when used to perform gas-phase etching of silicon regions following conditioning. Alternatively, a hydrogen-containing precursor may be remotely or locally excited in a plasma to treat the interior chamber walls in embodiments. Regions of exposed silicon may then be etched with more reproducible etch rates from wafer-to-

2

wafer. The silicon etch may be performed using plasma effluents formed from a remotely excited fluorine-containing precursor.

Embodiments of the invention include methods of conditioning a substrate processing region. The methods include exciting a conditioning fluorine-containing precursor in a conditioning plasma to produce conditioning plasma effluents. The methods further include exposing interior processing chamber walls to the conditioning plasma effluents. The interior processing chamber walls border a substrate processing region.

Embodiments of the invention include methods of conditioning a substrate processing region. The methods include exciting a hydrogen-containing precursor in a conditioning plasma to produce conditioning plasma effluents. The methods further include exposing interior processing chamber walls to the conditioning plasma effluents. The interior processing chamber walls border a substrate processing region.

Additional embodiments and features are set forth in part in the description that follows, and in part will become apparent to those skilled in the art upon examination of the specification or may be learned by the practice of the disclosed embodiments. The features and advantages of the disclosed embodiments may be realized and attained by means of the instrumentalities, combinations, and methods described in the specification.

DESCRIPTION OF THE DRAWINGS

A further understanding of the nature and advantages of the disclosed embodiments may be realized by reference to the remaining portions of the specification and the drawings.

FIG. 1 is a flow chart of a preventative maintenance procedure according to embodiments.

FIG. 2 is a flow chart of a preventative maintenance procedure according to embodiments.

FIG. 3 is a plot of silicon etch rates without a preventative maintenance procedure and following a preventative maintenance procedure according to embodiments.

FIG. 4A shows a substrate processing chamber according to embodiments of the invention.

FIG. 4B shows a showerhead of a substrate processing chamber according to embodiments of the invention.

FIG. 5 shows a substrate processing system according to embodiments of the invention.

In the appended figures, similar components and/or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If only the first reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

DETAILED DESCRIPTION

Methods of conditioning interior processing chamber walls of an etch chamber are described. A fluorine-containing precursor may be remotely or locally excited in a plasma to treat the interior chamber walls periodically on a preventative maintenance schedule. The treated walls promote an even etch rate when used to perform gas-phase etching of silicon regions following conditioning. Alternatively, a hydrogen-containing precursor may be remotely or locally excited in a plasma to treat the interior chamber walls in

embodiments. Regions of exposed silicon may then be etched with more reproducible etch rates from wafer-to-wafer. The silicon etch may be performed using plasma effluents formed from a remotely excited fluorine-containing precursor.

In order to better understand and appreciate the invention, reference is now made to FIG. 1 which is a preventative maintenance procedure 100 according to embodiments. No substrate or a "dummy" substrate may be present in the substrate processing region during the first three operations of FIG. 1 according to embodiments. Preventative maintenance procedure 100 reduces cost by not relying on the presence of a substrate during the preventative maintenance operations. Nitrogen trifluoride is flowed into a remote plasma region and a remote plasma power is applied (operation 110) to form conditioning plasma effluents. The remote plasma region is separate from the processing region. The conditioning plasma effluents are flowed into the substrate processing region (operation 120). Other sources of fluorine may be used to augment or replace the nitrogen trifluoride. In general, a conditioning fluorine-containing precursor may be flowed into the remote plasma region and the conditioning fluorine-containing precursor may include one or more of atomic fluorine, diatomic fluorine, boron trifluoride, chlorine trifluoride, nitrogen trifluoride, fluorinated hydrocarbons, sulfur hexafluoride and xenon difluoride. The conditioning plasma effluents treat the interior chamber walls (operation 125) by chemically altering the surfaces.

The last three operations of FIG. 1 are optional but help make the benefits of the first three operations more clear. A substrate having exposed regions of silicon is then delivered into the substrate processing region (operation 130). The substrate may be a patterned substrate and may have additional exposed regions (e.g. of silicon oxide) in embodiments. A flow of nitrogen trifluoride is introduced into the remote plasma region. Other sources of fluorine may be used to augment or replace the nitrogen trifluoride. In general, an etching fluorine-containing precursor may be flowed into the remote plasma region and the etching fluorine-containing precursor may include one or more of atomic fluorine, diatomic fluorine, boron trifluoride, chlorine trifluoride, nitrogen trifluoride, hydrogen fluoride, perfluorinated hydrocarbons, sulfur hexafluoride and xenon difluoride. Nitrogen trifluoride offers a particular benefit since it forms long-lived radical-fluorine in the conditioning plasma effluents and the etching plasma effluents discussed shortly. Radical-fluorine formed from nitrogen trifluoride remains highly reactive even after passing through showerheads and/or ion suppression elements described herein.

The remote plasma region may be located within a distinct module separate from the processing chamber or a compartment within the processing chamber. The separate plasma region may be fluidly coupled to the substrate processing region by through-holes in a showerhead disposed between the two regions. The hardware just described (and elaborated on in the equipment section) may also be used in all processes discussed herein.

The etching plasma effluents formed in the remote plasma region are then flowed into the substrate processing region through the through-holes the showerhead separating the remote plasma region and the substrate processing region. Silicon on the substrate is selectively etched (operation 135) such that silicon may be removed more rapidly than a variety of other materials. The etch selectivity (silicon:silicon oxide or silicon:silicon nitride) may also be greater than or about 70:1, greater than or about 100:1, greater than or about 150:1, greater than or about 200:1, greater than or about

250:1 or greater than or about 300:1 according to embodiments. Regions of exposed tungsten or titanium nitride may be present, in embodiments, on the patterned substrate and may be referred to as exposed metallic regions. The etch selectivity (silicon:exposed metallic region) may be greater than or about 100:1, greater than or about 150:1, greater than or about 200:1, greater than or about 250:1, greater than or about 500:1, greater than or about 1000:1, greater than or about 2000:1 or greater than or about 3000:1 according to embodiments. The reactive chemical species and any process effluents are removed from the substrate processing region and then the substrate is removed from the substrate processing region (operation 145).

The conditioning of the interior processing chamber walls of bordering the substrate processing region enables the selective etch rate to remain more uniform from wafer to wafer for an extended period of time. The improvement suggests that the chemical termination on the interior processing chamber walls is more stable rather than evolving over time. A qualitative description of the etch rate in comparison to that attained using unconditioned walls will be described along with FIG. 3.

The flow rate ranges now given for conditioning and etching fluorine-containing precursors apply to each of flowing operation 110 and selective etching operation 135 (as well as all etching operations described herein). In embodiments, the fluorine-containing precursor (e.g. NF_3) is supplied at a flow rate of between about 5 sccm and about 500 sccm, between about 10 sccm and about 300 sccm, between about 25 sccm and about 200 sccm, between about 50 sccm and about 150 sccm or between about 75 sccm and about 125 sccm. The substrate processing region and the remote plasma region may be devoid of or essentially devoid of hydrogen during treatment operation 125 in embodiments. Similarly, the substrate processing region and the remote plasma region may be devoid of or essentially devoid of hydrogen during selective etching operation 135 according to embodiments. Alternatively, a very high hydrogen:fluorine atomic flow ratio (e.g. H:F greater than ten) may be used during selective etching operation 135 (and other etching operations described herein) to selectively etch silicon relative to a broader array of materials.

The method also includes applying energy to the conditioning and etching fluorine-containing precursor in the remote plasma region to generate the conditioning and etching plasma effluents in each of remote plasma operation 110 and selective etching operation 135 (as well as all remote plasmas described herein). The plasma may be generated using known techniques (e.g., radio frequency excitations, capacitively-coupled power, inductively coupled power). In an embodiment, the energy may be applied using a capacitively-coupled plasma unit. The remote plasma source power may be between about 100 watts and about 3000 watts, between about 200 watts and about 2000 watts, between about 300 watts and about 1000 watts in embodiments. Treatment operation 125 (and all treatment operations described herein) may also involve a local plasma excitation instead of or in addition to the remote plasma excitation according to embodiments. The plasma powers of local plasmas used to perform treatment operations herein may involve application of the same plasma powers as the remote plasmas in embodiments. Local plasmas may alternatively be referred to herein as "direct" plasmas. When a local plasma is used to replace operations 110-120, the substrate processing region may be devoid of or essentially devoid of hydrogen in embodiments. Plasmas may be referred to as "conditioning plasmas"

5

during application of the treatment plasma (operation 110) or may be referred to as "etching plasmas" or "remote etching plasmas" during selective etching operation 135. Conditioning plasmas may be referred to as "remote conditioning plasmas" or "local conditioning plasmas" to describe where the plasma is located.

Reference is now made to FIG. 2 which is a preventative maintenance procedure 200 according to embodiments. The various traits and process parameters discussed with reference to FIG. 1 may not be repeated here except when they deviate from those traits and process parameters. No substrate or a "dummy" substrate may be present in the substrate processing region during the first three operations of FIG. 2 according to embodiments. Preventative maintenance procedure 200 reduces cost by not relying on the presence of a substrate during the preventative maintenance operations. Ammonia is flowed into a substrate processing region (operation 210) and a local plasma power is applied (operation 220) to treat the interior processing chamber walls bordering the substrate processing region (operation 225). Despite the local nature of the plasma, the plasma effluents impact and treat the interior chamber walls (operation 225) by chemically altering the surfaces. The substrate processing region may be devoid of or essentially devoid of fluorine during treatment operation 225 according to embodiments. In general a hydrogen-containing precursor or a nitrogen-and-hydrogen-containing precursor (which may consist of nitrogen and hydrogen) may be flowed into the substrate processing region in operation 210. A nitrogen-and-hydrogen-containing precursor may include one or both of ammonia and hydrazine according to embodiments, and may be devoid of fluorine according to embodiments.

The last three optional operations of FIG. 2 are again included to improve understanding of the impact of treatment operation 225. A substrate having exposed regions of silicon is then delivered into the substrate processing region (operation 230). The substrate may be a patterned substrate and may have additional exposed regions (e.g. of silicon oxide) in embodiments. A flow of nitrogen trifluoride is introduced into a remote plasma region. Other sources of fluorine may be used to augment or replace the nitrogen trifluoride. In general, a fluorine-containing precursor may be flowed into the remote plasma region and the fluorine-containing precursor may include one or more of atomic fluorine, diatomic fluorine, boron trifluoride, chlorine trifluoride, nitrogen trifluoride, hydrogen fluoride, fluorinated hydrocarbons, sulfur hexafluoride and xenon difluoride. As before, nitrogen trifluoride is used in a preferred embodiment owing to the formation of long-lived radical-fluorine in the plasma effluents. The fluorine-containing precursor may be devoid of hydrogen according to embodiments.

The remote plasma region herein may be within a distinct module from the processing chamber or a compartment within the processing chamber according to embodiments. The separate plasma region may be fluidly coupled to the substrate processing region by through-holes in a showerhead disposed between the two regions. The plasma effluents formed in the remote plasma region are then flowed into the substrate processing region through the through-holes the showerhead. Silicon on the substrate is selectively etched (operation 235) such that silicon may be removed more rapidly than a variety of other materials. The remote plasma region and the substrate processing region may be devoid of hydrogen during selective etching operation 235 according to embodiments. The etch selectivity described earlier apply to selective etching operation 235 as well. The reactive chemical species and any process effluents are removed

6

from the substrate processing region and then the substrate is removed from the substrate processing region (operation 245).

The conditioning of the interior processing chamber walls in preventative maintenance procedure 200 may result in a chemically distinct layer formed on the interior surfaces bordering the substrate processing region when compared with preventative maintenance procedure 100.

The etch rate, however, may be more similar from wafer to wafer relative to etch rates obtained using untreated chamber walls bordering the substrate processing region. The treated chamber walls enable the etch rate to remain more uniform from wafer to wafer for an extended period of time (e.g. days). The improvement suggests that the chemical termination on the interior processing chamber walls, though distinct from the treatment of FIG. 1, is still more stable rather than evolving over time (e.g. from one substrate to a subsequently processed substrate).

Flow rates for the fluorine-containing precursor were given earlier and are not repeated here. The flow rate ranges for the hydrogen-containing precursor in treatment operation 225 are now described since no hydrogen-containing precursor was present in preventative maintenance procedure 100. The hydrogen-containing precursor (e.g. NH_3) is supplied at a flow rate of between about 5 sccm and about 500 sccm, between about 10 sccm and about 300 sccm, between about 25 sccm and about 200 sccm, between about 50 sccm and about 150 sccm or between about 75 sccm and about 125 sccm according to embodiments.

The method also includes applying energy to the hydrogen-containing precursor in the substrate processing region to generate the plasma effluents which treat the interior chamber walls bordering the substrate processing region in treatment operation 125. The plasma may be generated using known techniques (e.g., radio frequency excitations, capacitively-coupled power, inductively coupled power). In an embodiment, the energy may be applied using a capacitively-coupled plasma unit. The local plasma power may be between about 100 watts and about 3000 watts, between about 200 watts and about 2000 watts, between about 300 watts and about 1000 watts in embodiments. Treatment operation 125 (and all treatment operations described herein) may also involve a remote plasma excitation instead of or in addition to the local plasma excitation according to embodiments. The plasma powers of remote plasmas used to perform treatment operations herein may involve application of the same plasma powers as the local plasmas in embodiments. When a remote plasma is used, the substrate processing region and the remote plasma region may be devoid of or essentially devoid of fluorine according to embodiments.

In all embodiments described herein which use a remote plasma, the term "plasma-free" may be used to describe the substrate processing region during application of no or essentially no plasma power. A plasma-free substrate processing region may be used for both treatment operations (operations 125 and 225) and selective etching operations (operations 135 and 235) in embodiments.

The temperature of the substrate for all embodiments described herein may be greater than 0° C. during the etch process. The substrate temperature may be greater than or about 20° C. and less than or about 300° C. At the high end of this substrate temperature range, the silicon etch rate drops. At the lower end of this substrate temperature range, silicon oxide and silicon nitride begin to etch and so the selectivity drops. In disclosed embodiments, the temperature of the substrate during the etches described herein may be

greater than or about 30° C. while less than or about 200° C. or greater than or about 40° C. while less than or about 150° C. The substrate temperature may be below 100° C., below or about 80° C., below or about 65° C. or below or about 50° C. in disclosed embodiments.

The data further show an increase in silicon etch rate as a function of process pressure during selective etching operations **135** and **235**. This is suspected to result from a higher probability of combining two or more fluorine-containing effluents. The etch process then begins to remove silicon oxide, silicon nitride and other materials. The pressure within the substrate processing region may be below or about 10 Torr, below or about 5 Torr, below or about 3 Torr, below or about 2 Torr, below or about 1 Torr or below or about 750 mTorr according to embodiments. In order to ensure adequate etch rate, the pressure may be above or about 0.05 Torr, above or about 0.1 Torr, above or about 0.2 Torr or above or about 0.4 Torr in embodiments. Any of the upper limits on pressure may be combined with lower limits according to embodiments.

A pre-treatment may be used, in embodiments, to remove a thin oxide layer on the surfaces of the exposed silicon regions. The pre-treatment occurs before selectively etching the silicon (operations **135** or **235**). Thin oxide layers often form when exposing silicon to oxygen in one form or another (e.g. atmospheric conditions). The thin oxide layer can make the silicon regions behave more like silicon oxide regions, in part, because the selectivities of the processes reported herein are so high. The thin silicon oxide layer is often referred to as a “native” oxide and may be removed using a variety of processes known to those of skill in the art. For example, a Siconi™ etch may be used to remove the native oxide. In other words, a fluorine-containing precursor and a hydrogen-containing precursor may be combined in a remote plasma region and excited in a plasma. The atomic flow ratio H:F during the pre-treatment Siconi™ may be between about 0.5:1 and about 8:1 to ensure the production of solid by-products on the exposed silicon surfaces. The native oxide is consumed during the production of these solid by-products in embodiments of the invention. The temperature of the patterned substrate during the Siconi™ etch may be below the sublimation temperature of the solid by-products. The temperature of the patterned substrate may be raised above the sublimation temperature after formation of the solid by-products to remove the solid by-products. The sublimation completes the removal of the native oxide from the exposed silicon.

Alternatively, the native oxide can be removed by a hydrogen plasma formed in the substrate processing region. The local pre-treatment plasma is created by applying a local plasma power above or about 200 watts and below or about 3000 watts or above or about 300 watts and below or about 2000 watts in embodiments. Regardless of the method used, the native oxide (if present) is removed before the operation of etching the exposed silicon. Techniques for removing the native oxide may be carried out in the same substrate processing region used to selectively etch the silicon, or each of these processes may be performed in separate chambers. However, the patterned substrate should not be exposed to moisture or an atmospheric environment during the transfer between separate chambers. It should also be noted that the terms “exposed silicon region” and “exposed silicon” will be used herein regardless of whether a native oxide is present.

An advantage of the processes described herein lies in the conformal rate of removal of metal-containing material from the substrate. The methods do not rely on a bias power to accelerate etchants towards the substrate, which reduces the

tendency of the etch processes to remove material on the tops and bottom of trenches before material on the sidewalls can be removed. As used herein, a conformal etch process refers to a generally uniform removal rate of material from a patterned surface regardless of the shape of the surface. The surface of the layer before and after the etch process are generally parallel. A person having ordinary skill in the art will recognize that the etch process likely cannot be 100% conformal and thus the term “generally” allows for acceptable tolerances.

In each remote plasma or local plasma described herein, the flows of the precursors into the remote plasma region may further include one or more relatively inert gases such as He, N₂, Ar. The inert gas can be used to improve plasma stability, ease plasma initiation, and improve process uniformity. Argon is helpful, as an additive, to promote the formation of a stable plasma. Process uniformity is generally increased when helium is included. These additives are present in embodiments throughout this specification. Flow rates and ratios of the different gases may be used to control etch rates and etch selectivity.

In embodiments, an ion suppressor as described in the exemplary equipment section may be used to provide radical and/or neutral species for selectively etching substrates. The ion suppressor may also be referred to as an ion suppression element. In embodiments, for example, the ion suppressor is used to filter fluorine-containing plasma effluents to selectively etch silicon. The ion suppressor may be included in each exemplary process described herein. Using the plasma effluents, an etch rate selectivity of metal-containing material to a wide variety of materials may be achieved.

The ion suppressor may be used to provide a reactive gas having a higher concentration of radicals than ions. The ion suppressor functions to dramatically reduce or substantially eliminate ionically charged species traveling from the plasma generation region to the substrate. The electron temperature may be measured using a Langmuir probe in the substrate processing region during excitation of a plasma in the remote plasma region on the other side of the ion suppressor. In embodiments, the electron temperature may be less than 0.5 eV, less than 0.45 eV, less than 0.4 eV, or less than 0.35 eV. These extremely low values for the electron temperature are enabled by the presence of the showerhead and/or the ion suppressor positioned between the substrate processing region and the remote plasma region. Uncharged neutral and radical species may pass through the openings in the ion suppressor to react at the substrate. Because most of the charged particles of a plasma are filtered or removed by the ion suppressor, the substrate is not necessarily biased during the etch process. Such a process using radicals and other neutral species can reduce plasma damage compared to conventional plasma etch processes that include sputtering and bombardment. The ion suppressor helps control the concentration of ionic species in the reaction region at a level that assists the process. Embodiments of the present invention are also advantageous over conventional wet etch processes where surface tension of liquids can cause bending and peeling of small features.

FIG. **3** is a plot of silicon etch rates **300** without a preventative maintenance procedure and following a preventative maintenance procedure according to embodiments. The plot of silicon etch rates **300** includes etch rate measurements performed over a sequence of 900 wafers (an example of substrates). Data **310** are included showing changes to etch rate of silicon over time while processing a sequence of wafers without any treatment operation prior to processing the wafers. The etch rate can be shown drifting

upward as, presumably, the interior surfaces bordering the substrate processing region evolve over time. Data 320 are also included which show a relatively stable silicon etch rate following treatment operation 125 (using a fluorine-containing precursor). Data 330 are also included which show a relatively silicon etch rate following treatment 225 (using a hydrogen-containing precursor). The data following fluorine treatment operation 125 and the data following hydrogen treatment operation 225 are both indicative of a stable silicon etch rate which are each desirable in a manufacturing environment. Note that the magnitude of the etch rate following each of the two preventative maintenance operations differ from one another, presumably because the surfaces are covered with different chemical species. The interior surfaces bordering the substrate processing region are coated after fluorine treatment operation 125 such that the etch rate is stable at a value similar to the first wafer processed in an untreated chamber (the left-most data point in untreated data 310). The interior surfaces are coated after hydrogen treatment operation 225 such that the etch rate is stable at a higher silicon etch rate which roughly matches the asymptotic extension of the etch rates for untreated data 310 after a large number of wafers is processed. The appropriate preventative maintenance procedure may be selected based on a variety of process characteristics such as magnitude of etch rate, particle performance and etch rate within-wafer uniformity.

Additional process parameters are disclosed in the course of describing an exemplary processing chamber and system. Exemplary Processing System

Processing chambers that may implement embodiments of the present invention may be included within processing platforms such as the CENTURA® and PRODUCER® systems, available from Applied Materials, Inc. of Santa Clara, Calif.

FIG. 4A is a substrate processing chamber 1001 according to embodiments. A remote plasma system 1010 may process a fluorine-containing precursor and/or a hydrogen-containing precursor which then travels through a gas inlet assembly 1011. Two distinct gas supply channels are visible within the gas inlet assembly 1011. A first channel 1012 carries a gas that passes through the remote plasma system 1010 (RPS), while a second channel 1013 bypasses the remote plasma system 1010. Either channel may be used for the fluorine-containing precursor, in embodiments. On the other hand, the first channel 1012 may be used for the process gas and the second channel 1013 may be used for a treatment gas. The lid (or conductive top portion) 1021 and a perforated partition 1053 are shown with an insulating ring 1024 in between, which allows an AC potential to be applied to the lid 1021 relative to perforated partition 1053. The AC potential strikes a plasma in chamber plasma region 1020. The process gas may travel through first channel 1012 into chamber plasma region 1020 and may be excited by a plasma in chamber plasma region 1020 alone or in combination with remote plasma system 1010. If the process gas (the fluorine-containing precursor) flows through second channel 1013, then only the chamber plasma region 1020 is used for excitation. The combination of chamber plasma region 1020 and/or remote plasma system 1010 may be referred to as a remote plasma region herein. The perforated partition (also referred to as a showerhead) 1053 separates chamber plasma region 1020 from a substrate processing region 1070 beneath showerhead 1053. Showerhead 1053 allows a plasma present in chamber plasma region 1020 to avoid directly exciting gases in substrate processing region

1070, while still allowing excited species to travel from chamber plasma region 1020 into substrate processing region 1070.

Showerhead 1053 is positioned between chamber plasma region 1020 and substrate processing region 1070 and allows plasma effluents (excited derivatives of precursors or other gases) created within remote plasma system 1010 and/or chamber plasma region 1020 to pass through a plurality of through-holes 1056 that traverse the thickness of the plate. The showerhead 1053 also has one or more hollow volumes 1051 which can be filled with a precursor in the form of a vapor or gas (such as a fluorine-containing precursor) and pass through blind-holes 1055 into substrate processing region 1070 but not directly into chamber plasma region 1020. Showerhead 1053 is thicker than the length of the smallest diameter 1050 of the through-holes 1056 in embodiments. To maintain a significant concentration of excited species penetrating from chamber plasma region 1020 to substrate processing region 1070, the length 1026 of the smallest diameter 1050 of the through-holes may be restricted by forming larger diameter portions of through-holes 1056 part way through the showerhead 1053. The length of the smallest diameter 1050 of the through-holes 1056 may be the same order of magnitude as the smallest diameter of the through-holes 1056 or less in embodiments. Showerhead 1053 may be referred to as a dual-channel showerhead, a dual-zone showerhead, a multi-channel showerhead or a multi-zone showerhead to convey the existence of through-holes and blind-holes for introducing precursors.

Showerhead 1053 may be configured to serve the purpose of an ion suppressor as shown in FIG. 4A. Alternatively, a separate processing chamber element may be included (not shown) which suppresses the ion concentration traveling into substrate processing region 1070. Lid 1021 and showerhead 1053 may function as a first electrode and second electrode, respectively, so that lid 1021 and showerhead 1053 may receive different electric voltages. In these configurations, electrical power (e.g., RF power) may be applied to lid 1021, showerhead 1053, or both. For example, electrical power may be applied to lid 1021 while showerhead 1053 (serving as ion suppressor) is grounded. The substrate processing system may include a RF generator that provides electrical power to the lid and/or showerhead 1053. The voltage applied to lid 1021 may facilitate a uniform distribution of plasma (i.e., reduce localized plasma) within chamber plasma region 1020. To enable the formation of a plasma in chamber plasma region 1020, insulating ring 1024 may electrically insulate lid 1021 from showerhead 1053. Insulating ring 1024 may be made from a ceramic and may have a high breakdown voltage to avoid sparking. Portions of substrate processing chamber 1001 near the capacitively-coupled plasma components just described may further include a cooling unit (not shown) that includes one or more cooling fluid channels to cool surfaces exposed to the plasma with a circulating coolant (e.g., water).

In the embodiment shown, showerhead 1053 may distribute (via through-holes 1056) process gases which contain fluorine, hydrogen and/or plasma effluents of such process gases upon excitation by a plasma in chamber plasma region 1020. In embodiments, the process gas introduced into the remote plasma system 1010 and/or chamber plasma region 1020 may contain fluorine. The process gas may also include a carrier gas such as helium, argon, nitrogen (N₂), etc. Plasma effluents may include ionized or neutral derivatives of the process gas and may also be referred to herein as

11

radical-fluorine and/or radical-hydrogen referring to the atomic constituent of the process gas introduced.

Through-holes **1056** are configured to suppress the migration of ionically-charged species out of the chamber plasma region **1020** while allowing uncharged neutral or radical species to pass through showerhead **1053** into substrate processing region **1070**. These uncharged species may include highly reactive species that are transported with less-reactive carrier gas by through-holes **1056**. As noted above, the migration of ionic species by through-holes **1056** may be reduced, and in some instances completely suppressed. Controlling the amount of ionic species passing through showerhead **1053** provides increased control over the gas mixture brought into contact with the underlying wafer substrate, which in turn increases control of the deposition and/or etch characteristics of the gas mixture. For example, adjustments in the ion concentration of the gas mixture can alter the etch selectivity (e.g., the silicon:silicon nitride etch rate ratio).

In embodiments, the number of through-holes **1056** may be between about 60 and about 2000. Through-holes **1056** may have a variety of shapes but are most easily made round. The smallest diameter **1050** of through-holes **1056** may be between about 0.5 mm and about 20 mm or between about 1 mm and about 6 mm in embodiments. There is also latitude in choosing the cross-sectional shape of through-holes, which may be made conical, cylindrical or combinations of the two shapes. The number of blind-holes **1055** used to introduce unexcited precursors into substrate processing region **1070** may be between about 100 and about 5000 or between about 500 and about 2000 in different embodiments. The diameter of the blind-holes **1055** may be between about 0.1 mm and about 2 mm.

Through-holes **1056** may be configured to control the passage of the plasma-activated gas (i.e., the ionic, radical, and/or neutral species) through showerhead **1053**. For example, the aspect ratio of the holes (i.e., the hole diameter to length) and/or the geometry of the holes may be controlled so that the flow of ionically-charged species in the activated gas passing through showerhead **1053** is reduced. Through-holes **1056** in showerhead **1053** may include a tapered portion that faces chamber plasma region **1020**, and a cylindrical portion that faces substrate processing region **1070**. The cylindrical portion may be proportioned and dimensioned to control the flow of ionic species passing into substrate processing region **1070**. An adjustable electrical bias may also be applied to showerhead **1053** as an additional means to control the flow of ionic species through showerhead **1053**.

Alternatively, through-holes **1056** may have a smaller inner diameter (ID) toward the top surface of showerhead **1053** and a larger ID toward the bottom surface. In addition, the bottom edge of through-holes **1056** may be chamfered to help evenly distribute the plasma effluents in substrate processing region **1070** as the plasma effluents exit the showerhead and promote even distribution of the plasma effluents and precursor gases. The smaller ID may be placed at a variety of locations along through-holes **1056** and still allow showerhead **1053** to reduce the ion density within substrate processing region **1070**. The reduction in ion density results from an increase in the number of collisions with walls prior to entry into substrate processing region **1070**. Each collision increases the probability that an ion is neutralized by the acquisition or loss of an electron from the wall. Generally speaking, the smaller ID of through-holes **1056** may be between about 0.2 mm and about 20 mm. In other embodiments, the smaller ID may be between about 1

12

mm and 6 mm or between about 0.2 mm and about 5 mm. Further, aspect ratios of the through-holes **1056** (i.e., the smaller ID to hole length) may be approximately 1 to 20. The smaller ID of the through-holes may be the minimum ID found along the length of the through-holes. The cross sectional shape of through-holes **1056** may be generally cylindrical, conical, or any combination thereof.

FIG. 4B is a bottom view of a showerhead **1053** for use with a processing chamber according to embodiments. Showerhead **1053** corresponds with the showerhead shown in FIG. 4A. Through-holes **1056** are depicted with a larger inner-diameter (ID) on the bottom of showerhead **1053** and a smaller ID at the top. Blind-holes **1055** are distributed substantially evenly over the surface of the showerhead, even amongst the through-holes **1056** which helps to provide more even mixing than other embodiments described herein.

An exemplary patterned substrate may be supported by a pedestal (not shown) within substrate processing region **1070** when fluorine-containing plasma effluents or hydrogen-containing plasma effluents arrive through through-holes **1056** in showerhead **1053**. Though substrate processing region **1070** may be equipped to support a plasma for other processes such as curing, no plasma is present during the etching of patterned substrate, in embodiments.

A plasma may be ignited either in chamber plasma region **1020** above showerhead **1053** or substrate processing region **1070** below showerhead **1053**. A plasma is present in chamber plasma region **1020** to produce the radical-fluorine from an inflow of the fluorine-containing precursor. An AC voltage typically in the radio frequency (RF) range is applied between the conductive top portion (lid **1021**) of the processing chamber and showerhead **1053** to ignite a plasma in chamber plasma region **1020** during deposition. An RF power supply generates a high RF frequency of 13.56 MHz but may also generate other frequencies alone or in combination with the 13.56 MHz frequency.

The top plasma may be left at low or no power when the bottom plasma in the substrate processing region **1070** is turned on to either cure a film or clean the interior surfaces bordering substrate processing region **1070**. A plasma in substrate processing region **1070** is ignited by applying an AC voltage between showerhead **1053** and the pedestal or bottom of the chamber. A cleaning gas may be introduced into substrate processing region **1070** while the plasma is present.

The pedestal may have a heat exchange channel through which a heat exchange fluid flows to control the temperature of the substrate. This configuration allows the substrate temperature to be cooled or heated to maintain relatively low temperatures (from room temperature through about 120° C.). The heat exchange fluid may comprise ethylene glycol and water. The wafer support platter of the pedestal (preferably aluminum, ceramic, or a combination thereof) may also be resistively heated to achieve relatively high temperatures (from about 120° C. through about 1100° C.) using an embedded single-loop embedded heater element configured to make two full turns in the form of parallel concentric circles. An outer portion of the heater element may run adjacent to a perimeter of the support platter, while an inner portion runs on the path of a concentric circle having a smaller radius. The wiring to the heater element passes through the stem of the pedestal.

The chamber plasma region and/or a region in a remote plasma system may be referred to as a remote plasma region. In embodiments, the radical precursors (e.g. radical-fluorine and/or radical-hydrogen) are formed in the remote plasma

13

region and travel into the substrate processing region where they may individually react with chamber walls or the substrate surface. Plasma power may essentially be applied only to the remote plasma region, in embodiments, to ensure that the radical-fluorine or the radical-hydrogen (which may also be referred to as plasma effluents) are not further excited in the substrate processing region.

In embodiments employing a chamber plasma region, the excited plasma effluents are generated in a section of the substrate processing region partitioned from a deposition region. The deposition region, also known herein as the substrate processing region, is where the plasma effluents mix and react to etch the patterned substrate (e.g., a semiconductor wafer). The excited plasma effluents may also be accompanied by inert gases (in the exemplary case, argon). The substrate processing region may be described herein as "plasma-free" during etching of the substrate. "Plasma-free" does not necessarily mean the region is devoid of plasma. A relatively low concentration of ionized species and free electrons created within the remote plasma region do travel through pores (apertures) in the partition (showerhead/ion suppressor) due to the shapes and sizes of through-holes 1056. In some embodiments, there is essentially no concentration of ionized species and free electrons within the substrate processing region. In embodiments, the electron temperature may be less than 0.5 eV, less than 0.45 eV, less than 0.4 eV, or less than 0.35 eV in substrate processing region 1070 during excitation of a remote plasma. The borders of the plasma in the chamber plasma region are hard to define and may encroach upon the substrate processing region through the apertures in the showerhead. In the case of an inductively-coupled plasma, a small amount of ionization may be effected within the substrate processing region directly. Furthermore, a low intensity plasma may be created in the substrate processing region without eliminating desirable features of the forming film. All causes for a plasma having much lower intensity ion density than the chamber plasma region (or a remote plasma region, for that matter) during the creation of the excited plasma effluents do not deviate from the scope of "plasma-free" as used herein.

The fluorine-containing precursor may be flowed into chamber plasma region 1020 at rates between about 5 sccm and about 500 sccm, between about 10 sccm and about 300 sccm, between about 25 sccm and about 200 sccm, between about 50 sccm and about 150 sccm or between about 75 sccm and about 125 sccm in embodiments.

The flow rate of the fluorine-containing precursor into the chamber may account for 0.05% to about 20% by volume of the overall gas mixture; the remainder being carrier gases. The fluorine-containing precursor are flowed into the remote plasma region but the plasma effluents have the same volumetric flow ratio, in embodiments. A purge or carrier gas may be initiated into the remote plasma region before that of the fluorine-containing gas to stabilize the pressure within the remote plasma region.

Plasma power applied to the remote plasma region can be a variety of frequencies or a combination of multiple frequencies. In the exemplary processing system the plasma is provided by RF power delivered between lid 1021 and showerhead 1053. In an embodiment, the energy is applied using a capacitively-coupled plasma unit. When using a Frontier™ or similar system, the remote plasma source power may be between about 100 watts and about 3000 watts, between about 200 watts and about 2500 watts, between about 300 watts and about 2000 watts, or between about 500 watts and about 1500 watts in embodiments. The RF frequency applied in the exemplary processing system

14

may be low RF frequencies less than about 200 kHz, high RF frequencies between about 10 MHz and about 15 MHz or microwave frequencies greater than or about 1 GHz in embodiments.

Substrate processing region 1070 can be maintained at a variety of pressures during the flow of carrier gases and plasma effluents into substrate processing region 1070. The pressure within the substrate processing region is below or about 50 Torr, below or about 30 Torr, below or about 20 Torr, below or about 10 Torr or below or about 5 Torr. The pressure may be above or about 0.1 Torr, above or about 0.2 Torr, above or about 0.5 Torr or above or about 1 Torr in embodiments. Lower limits on the pressure may be combined with upper limits on the pressure to obtain embodiments.

In one or more embodiments, the substrate processing chamber 1001 can be integrated into a variety of multi-processing platforms, including the Producer™ GT, Centura™ AP and Endura™ platforms available from Applied Materials, Inc. located in Santa Clara, Calif. Such a processing platform is capable of performing several processing operations without breaking vacuum. Processing chambers that may implement embodiments of the present invention may include dielectric etch chambers or a variety of chemical vapor deposition chambers, among other types of chambers.

Embodiments of the etching systems may be incorporated into larger fabrication systems for producing integrated circuit chips. FIG. 5 shows one such system 1101 of etching, deposition, baking and curing chambers according to embodiments. In the figure, a pair of FOUPs (front opening unified pods) 1102 supply substrate substrates (e.g., 300 mm diameter wafers) that are received by robotic arms 1104 and placed into a low pressure holding areas 1106 before being placed into one of the wafer processing chambers 1108a-f. A second robotic arm 1110 may be used to transport the substrate wafers from the low pressure holding areas 1106 to the wafer processing chambers 1108a-f and back. Each wafer processing chamber 1108a-f, can be outfitted to perform a number of substrate processing operations including the dry etch processes described herein in addition to cyclical layer deposition (CLD), atomic layer deposition (ALD), chemical vapor deposition (CVD), physical vapor deposition (PVD), etch, pre-clean, degas, orientation and other substrate processes.

The wafer processing chambers 1108a-f may include one or more system components for depositing, annealing, curing and/or etching a dielectric film on the substrate wafer. In one configuration, two pairs of the processing chamber (e.g., 1108c-d and 1108e-f) may be used to deposit dielectric material on the substrate, and the third pair of processing chambers (e.g., 1108a-b) may be used to etch the deposited dielectric. In another configuration, all three pairs of chambers (e.g., 1108a-f) may be configured to etch a dielectric film on the substrate. Any one or more of the processes described may be carried out on chamber(s) separated from the fabrication system shown in different embodiments.

The substrate processing system is controlled by a system controller. In an exemplary embodiment, the system controller includes a hard disk drive, a floppy disk drive and a processor. The processor contains a single-board computer (SBC), analog and digital input/output boards, interface boards and stepper motor controller boards. Various parts of CVD system conform to the Versa Modular European (VME) standard which defines board, card cage, and con-

15

nector dimensions and types. The VME standard also defines the bus structure as having a 16-bit data bus and a 24-bit address bus.

System controller **1157** is used to control motors, valves, flow controllers, power supplies and other functions required to carry out process recipes described herein. A gas handling system **1155** may also be controlled by system controller **1157** to introduce gases to one or all of the wafer processing chambers **1108a-f**. System controller **1157** may rely on feedback from optical sensors to determine and adjust the position of movable mechanical assemblies in gas handling system **1155** and/or in wafer processing chambers **1108a-f**. Mechanical assemblies may include the robot, throttle valves and susceptors which are moved by motors under the control of system controller **1157**.

In an exemplary embodiment, system controller **1157** includes a hard disk drive (memory), USB ports, a floppy disk drive and a processor. System controller **1157** includes analog and digital input/output boards, interface boards and stepper motor controller boards. Various parts of multi-chamber processing system **1101** which contains substrate processing chamber **1001** are controlled by system controller **1157**. The system controller executes system control software in the form of a computer program stored on computer-readable medium such as a hard disk, a floppy disk or a flash memory thumb drive. Other types of memory can also be used. The computer program includes sets of instructions that dictate the timing, mixture of gases, chamber pressure, chamber temperature, RF power levels, susceptor position, and other parameters of a particular process.

A process for etching, depositing or otherwise processing a film on a substrate or a process for cleaning chamber can be implemented using a computer program product that is executed by the controller. The computer program code can be written in any conventional computer readable programming language: for example, 68000 assembly language, C, C++, Pascal, Fortran or others. Suitable program code is entered into a single file, or multiple files, using a conventional text editor, and stored or embodied in a computer usable medium, such as a memory system of the computer. If the entered code text is in a high level language, the code is compiled, and the resultant compiler code is then linked with an object code of precompiled Microsoft Windows® library routines. To execute the linked, compiled object code the system user invokes the object code, causing the computer system to load the code in memory. The CPU then reads and executes the code to perform the tasks identified in the program.

The interface between a user and the controller may be via a touch-sensitive monitor and may also include a mouse and keyboard. In one embodiment two monitors are used, one mounted in the clean room wall for the operators and the other behind the wall for the service technicians. The two monitors may simultaneously display the same information, in which case only one is configured to accept input at a time. To select a particular screen or function, the operator touches a designated area on the display screen with a finger or the mouse. The touched area changes its highlighted color, or a new menu or screen is displayed, confirming the operator's selection.

As used herein "substrate" may be a support substrate with or without layers formed thereon. The patterned substrate may be an insulator or a semiconductor of a variety of doping concentrations and profiles and may, for example, be a semiconductor substrate of the type used in the manufacture of integrated circuits. Exposed "silicon" of the patterned substrate is predominantly Si but may include minority

16

concentrations of other elemental constituents (e.g. nitrogen, oxygen, hydrogen, carbon). Exposed "silicon nitride" of the patterned substrate is predominantly Si_3N_4 but may include minority concentrations of other elemental constituents (e.g. oxygen, hydrogen, carbon). Exposed "silicon oxide" of the patterned substrate is predominantly SiO_2 but may include minority concentrations of other elemental constituents (e.g. nitrogen, hydrogen, carbon). In some embodiments, silicon oxide films etched using the methods disclosed herein consist essentially of silicon and oxygen. "Titanium nitride" is predominantly titanium and nitrogen but may include minority concentrations of other elemental constituents (e.g. oxygen, hydrogen, carbon). Titanium nitride may consist essentially of titanium and nitrogen. "Tungsten oxide" is predominantly tungsten and oxygen but may include minority concentrations of other elemental constituents (e.g. nitrogen, hydrogen, carbon). Titanium nitride may consist essentially of tungsten and oxygen. "Tungsten" is predominantly tungsten but may include minority concentrations of other elemental constituents (e.g. nitrogen, oxygen, hydrogen, carbon).

The term "precursor" is used to refer to any process gas which takes part in a reaction to either remove material from or deposit material onto a surface. "Plasma effluents" describe gas exiting from the chamber plasma region and entering the substrate processing region. Plasma effluents are in an "excited state" wherein at least some of the gas molecules are in vibrationally-excited, dissociated and/or ionized states. A "radical precursor" is used to describe plasma effluents (a gas in an excited state which is exiting a plasma) which participate in a reaction to either remove material from or deposit material on a surface. "Radical-fluorine" (or "radical-hydrogen") are radical precursors which contain fluorine (or hydrogen) but may contain other elemental constituents. The phrase "inert gas" refers to any gas which does not form chemical bonds when etching or being incorporated into a film. Exemplary inert gases include noble gases but may include other gases so long as no chemical bonds are formed when (typically) trace amounts are trapped in a film.

The terms "gap" and "trench" are used throughout with no implication that the etched geometry has a large horizontal aspect ratio. Viewed from above the surface, trenches may appear circular, oval, polygonal, rectangular, or a variety of other shapes. A trench may be in the shape of a moat around an island of material. The term "via" is used to refer to a low aspect ratio trench (as viewed from above) which may or may not be filled with metal to form a vertical electrical connection. As used herein, a conformal etch process refers to a generally uniform removal of material on a surface in the same shape as the surface, i.e., the surface of the etched layer and the pre-etch surface are generally parallel. A person having ordinary skill in the art will recognize that the etched interface likely cannot be 100% conformal and thus the term "generally" allows for acceptable tolerances.

Having disclosed several embodiments, it will be recognized by those of skill in the art that various modifications, alternative constructions, and equivalents may be used without departing from the spirit of the disclosed embodiments. Additionally, a number of well-known processes and elements have not been described to avoid unnecessarily obscuring the present invention. Accordingly, the above description should not be taken as limiting the scope of the invention.

Where a range of values is provided, it is understood that each intervening value, to the tenth of the unit of the lower limit unless the context clearly dictates otherwise, between

17

the upper and lower limits of that range is also specifically disclosed. Each smaller range between any stated value or intervening value in a stated range and any other stated or intervening value in that stated range is encompassed. The upper and lower limits of these smaller ranges may independently be included or excluded in the range, and each smaller range where either, neither or both limits are included in the smaller ranges is also encompassed within the invention, subject to any specifically excluded limit in the stated range. Where the stated range includes one or both of the limits, ranges excluding either or both of those included limits are also included.

As used herein and in the appended claims, the singular forms “a”, “an”, and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a process” includes a plurality of such processes and reference to “the dielectric material” includes reference to one or more dielectric materials and equivalents thereof known to those skilled in the art, and so forth.

Also, the words “comprise,” “comprising,” “include,” “including,” and “includes” when used in this specification and in the following claims are intended to specify the presence of stated features, integers, components, or steps, but they do not preclude the presence or addition of one or more other features, integers, components, steps, acts, or groups.

The invention claimed is:

1. A method of conditioning a substrate processing region, the method comprising:

exciting a hydrogen-containing precursor in a conditioning plasma to produce conditioning plasma effluents; exposing interior processing chamber walls to the conditioning plasma effluents, wherein the interior processing chamber walls border a substrate processing region, wherein the substrate processing region is essentially devoid of fluorine during the operation of exposing the interior processing chamber walls to the conditioning plasma effluents;

performing multiple cycles of substrate etching, each cycle comprising:

(i) transferring a substrate into the substrate processing region following the operation of exposing the interior processing chamber walls to the conditioning plasma effluents, wherein the substrate comprises an exposed silicon portion;

18

(ii) flowing a fluorine-containing precursor into a remote plasma region fluidly coupled to the substrate processing region while forming a remote plasma in the remote plasma region to produce etching plasma effluents; and

(iii) selectively etching the exposed silicon portion by flowing the etching plasma effluents into the substrate processing region through through-holes in a showerhead, wherein the showerhead is disposed between the remote plasma region and the substrate processing region.

2. The method of claim 1 wherein the hydrogen-containing precursor is a nitrogen-and-hydrogen-containing precursor.

3. The method of claim 1 wherein the hydrogen-containing precursor comprises one or more of ammonia and hydrazine.

4. The method of claim 1 wherein the fluorine-containing precursor comprises one or more of atomic fluorine, diatomic fluorine, boron trifluoride, chlorine trifluoride, nitrogen, trifluoride, hydrogen fluoride, fluorinated hydrocarbons, sulfur hexafluoride and xenon difluoride.

5. The method of claim 1 wherein the conditioning plasma is a local conditioning plasma inside the substrate processing region.

6. The method of claim 1 wherein the conditioning plasma is a remote conditioning plasma outside the substrate processing region and the conditioning plasma effluents are flowed from the remote plasma into the substrate processing region.

7. The method of claim 1 wherein exposing interior processing chamber walls to the conditioning plasma effluents results in a chemical termination on the interior processing chamber walls.

8. The method of claim 7 wherein the multiple cycles of substrate etching does not cause the chemical termination on the interior processing chamber walls to evolve over time.

9. The method of claim 1 wherein each cycle of the multiple cycles of substrate etching remove a same etch amount of the exposed silicon portion.

10. The method of claim 1 wherein an etch rate of the exposed silicon portion does not evolve over time for over 900 cycles of substrate processing.

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